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ELECTRON BEAM EXCITED SUPERCONDUCTING
ANALOG-TO-DIGITAL CONVERTER

FIELD OF THE INVENTION

The present invention relates generally to analog to digital conversion, and more particularly to a system and a method for high-speed analog to digital conversions.

BACKGROUND OF THE INVENTION

Advances in digital processing are significantly impacting many endeavors in science and technology and digital processing applications. There are many situations which require converting fast analog signals into digital representation for processing and to harness the power of digital equipment. A key element is a device know as an analog-to-digital converter (A/D converter) which is a crucial front-end in many systems. However, the performance of A/D converters is lagging behind digital processors, creating an obstacle to full digitization of numerous applications.

It would be desirable to provide A/D converters operating between 30MHz and 3GHz with resolution in excess of about 10 bits. These A/D converters could be used as components in radar front-ends, intercept receivers, image processing, HDTV and in many other areas. Conventional semiconducting devices have well-known system limitations and cannot meet the above performance requirements. For instance, present silicon bipolar technology achieves 4 bits at 1GHz and GaAs heterojunction bipolar transistor (HBT) technology is projected to

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achieve 6 bits at 1GHz. This leaves Josephson junction (JJ) technology as the most promising to potentially produce the performance necessary for advanced digital systems.

The fastest Josephson junction flash A/D converter operated at liquid He temperature achieved 6 bits at 1GHz, and 3 bits at 10GHz. These low critical temperature (Tc) circuits require good quality Josephson junctions which have high non-linearity which cannot be reproduced using high Tc (HTC) superconductivity. Consequently, many known low Tc JJ circuits and concepts may not be implemented in HTC superconductivity. It is, therefore, safe to conclude that such known technologies reach their fundamental limitations at performance levels well below what is needed, and a search for new approaches is both warranted and timely.

Therefore, there remains a need in the art for a new A/D conversion system and method based on HTC superconductivity that produce performance levels orders of magnitude higher than what was thought possible using conventional low Tc JJ devices. In particular, a need exists for an A/D conversion system capable of bandwidths in excess of 10GHz at 10-bit resolution, which is impossible to achieve by previously-known technologies.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates the current – voltage characteristic of a weak link Josephson Junction device;

Fig. 2 illustrates an electron beam excited dispersionless HTC superconducting line matched at both ends and containing a weak links in series;

Fig. 3 illustrates a 3 bit electron beam excited superconducting A/D converter;

Fig. 4 illustrates a general, N-bit, beam excited superconducting A/D converter;

Fig. 5 illustrates expected performance of the exemplary embodiment electron beam analog to digital converter;

Fig. 6 shows a miniature Stirling closed cycle refrigerator; and

Fig. 7 illustrates a schematic diagram of an ultra-high performance analog to digital converter system.

SUMMARY OF THE INVENTION

The above-discussed and other problems and deficiencies of the prior art are overcome or alleviated by the several methods and apparatus of the present invention for a system and method for converting an analog voltage signal to a digital representation at high speeds, known as an analog to digital converter (A/D converter). The invention teaches an N-bit A/D converter, made by N superconducting, preferably HTC, transmission lines. The N lines are arranged adjacently and in parallel with each other. On each line 2^{N-1} JJs are imbedded in series. The JJs form a matrix over the configuration of the N superconducting transmission lines in such a manner that across the lines the JJs give N digit binary numbers, while in the length direction these N digit binary numbers fall in numerical order. A scanning electron beam is made to impinge on this arrangement. The beam is scanned across the lines at a high frequency, while it is deflected by the applied voltage signal along the direction of the lines. The beam generates a voltage step on any one of the N lines on condition of hitting any one of the JJs. In this manner upon each cross-scanning of the beam, an N-bit step voltage pattern is generated on the lines. This pattern is the direct digital readout of the input voltage signal.

The above-discussed and other features and advantages of the present invention will be

appreciated and understood by those skilled in the art from the following detailed description and

drawings.

DETAILED DESCRIPTION OF THE INVENTION

Herein disclosed is a novel A/D converter system and method that is based on HTC

superconductivity weak link devices which produce performance levels orders of magnitude

higher than what was thought possible using conventional low Tc Josephson junction (JJ)

devices. The system relies on two phenomena. First, that an electron beam is deflectable within

the many GHz frequency range. Second, that a Josephson Junction (JJ) switches into the voltage

state upon being hit by an appropriate electron beam. This ultra-high performance A/D

converter exploits the interaction of electron beams with superconducting devices and circuits.

In particular, the herein disclosed system and method is capable of deflecting electron beams at

bandwidths in excess of 10 GHz leading to A/D converter performance of 10 GHz bandwidth at

10-bit resolution. This is impossible to achieve with conventional technologies. This hybrid

system also benefits from the important dispersionless property of superconducting transmission

lines and ultra-fast switching of HTC weak links. In one embodiment, a 12-bit A/D converter

having an analog bandwidth of 500 MHz to 1GHz is possible. This is orders of magnitude

higher than other technologies. In yet another embodiment A/D converter performance can be

extended to 10GHz at 12 bits.

It is well known that Josephson junctions can be made to switch from the zero voltage

state to the finite voltage state when excited with an energetic electron beam. This beam

generates quasi-particles which suppress the Josephson current. Fig. 1 shows the current-voltage

characteristics of a JJ of the weak link type, which has a critical current J_0 and is current biased at

a current I_g. When the electron beam is applied, J_0 is suppressed to I'_0, well below I_g, causing the

device to switch from the zero voltage state to V_0. This device will reset back to the zero voltage

state upon removal of the electron beam excitation. The switching speed of weak link type JJ

devices is well known to be in the sub-picosecond range. To accomplish this, the energy of the

electron beam E_e must be in the order of the Josephson energy $E_j = I_0 M_0/2B$ at the same time, E_e

must be much smaller than the superconducting condensation energy. These conditions are

easily met using Josephson devices with I_0 in the range of 0.1 to 1 mA, and electron beam

currents and voltages of a few μA's and a few KV's, respectively, and the beam excitation pulse

duration in the 1-10 picosecond range.

Fig. 2 illustrates a transmission line 20 as a component of a multiple bit A/D converter

system disclosed herein. The transmission line 20 is a dispersionless HTC superconducting

transmission lines including plural Josephson junctions 22 in series (as represented by crosses in

Fig. 2). The transmission line 20 generally has a characteristic impedance of Z_0, (a few Ohms)

and is matched at both ends. A current supply biases the Josephson junctions at I_g, and, as shown

above, when an electron beam hits any one of these junctions, a voltage pulse V_0 is created and

transmitted to the output end of the line. This transmission line has a length L which defines the

propagation delay, T, of a signal from the left to the right and is given by $T = L/v_p$, where v_p, is

the transmission line phase velocity which, in practical situations, is equal to approximately one-

third the speed of light. The propagation delay generally limits the bandwidth and the bits of

resolution of the A/D converter.

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Accordingly, an A/D converter includes N transmission lines 20 described above in Fig. 2. The operating principles are illustrated in Fig. 3, wherein an embodiment of a 3-bit A/D converter 30 is depicted. In this case, three transmission lines 32a, 32b and 32c are placed adjacent to each other and separated by a suitable distance to minimize crosstalk. These transmission lines 32a, 32b and 32c are oriented along the Y direction and an electron beam is made to sweep or scan in the X direction. Also shown in Fig. 3 are 2^3, or eight, rows represented by Y_0 through Y_7. In the X, Y plane, a matrix identification thus created which has eight rows and three columns (three transmission lines 32a, 32b and 32c). A bit pattern representing the position of each row is shown by the number of Josephson junctions (cross symbol) in each row. For instance, the first row, Y_0, has no JJ's and the bit pattern representing the Y_0 position is (0,0,0). At the other end, Y_7, has 3 JJ's and the bit pattern is (1,1,1). To accomplish the A/D converter function one exploits the ability to scan an electron beam in the X and Y plane very rapidly. Electron beam deflection of bandwidths approaching 20GHz is possible. In the X direction, the electron beam is swept continuously at the sampling frequency f_s (f_s > 10 GHz). The input analog signal is applied to the Y deflection system, deflecting the beam in the Y direction, to any position between Y_0 and Y_7, depending on the value of the input analog signal. For instance, when the input analog signal is zero, the electron beam will be swept in the X direction across the first row (Y_0) and, in this case, because there are no Josephson junctions in this row, the output voltage of the three lines is the bit pattern (0.0.0). When the input voltage is highest, the beam is deflected in the Y direction so that it crosses the eighth row, Y_7, and three Josephson junctions will switch (according to Figures 1 and 2) and the output is the bit pattern (1,1,1). Of course, when the value is in between zero and the highest value, this will cause the

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beam to sweep across the other rows. As the analog signal varies, the output bit pattern changes

to reflect that at the sampling frequency f_s. It should be understood by one skilled in the art from

the herein description that it is arbitrary as to whether the JJs are assigned the digit of 1 and the

voids the digit of 0, or vice versa.

The 3-bit A/D converter 30 clearly relies on the zero resistance and dispersionless quality

of superconducting lines, the ultra-high switching speed of Josephson junctions and the ability to

deflect the electron beam in the X and Y direction in multiple GHz bandwidths.

In Fig. 4, a general A/D converter 40 for N bits is illustrated. Here, of course, N

transmission lines 42a, 42b, 42c...42_{N-1} are needed. The rows repeat at a period p, the length of

the JJ's, which is also the length of a unit of void, the shortest portion of the line without a JJ.

The total length of each transmission line is $L = p2^N$. This relationship clearly shows that if L is

maintained constant, as the value of p decreases, the number of bits increases, thus allowing for

a wider the analog bandwidth. The analog bandwidth is limited by the propagation delay T of

the signal in the transmission line 42, which is related to the length of the line. The bandwidth of

the A/D converter 40 may be expressed by: BW = 1/2T.

The sampling frequency is the frequency at which the electron beam is swept in the X

direction, and determines the ultimate performance of the system. The maximum analog

bandwidth BW of the system cannot be larger than ½ f_s. As shown in Figure 5, the performance

of the A/D converter is generally bounded by three lines or regions.

The flat region is limited by the performance of the electron beam deflection bandwidth

in the Y-direction, f_s and the relationship BW= f_s/2. The analog bandwidth BW=f_s/2 is

independent of the bits of resolution as long as the sampling period is longer than approximately

3T. For p = 0.5 micron and a beam size equal to 0.5 micron in diameter and f_s = 20 GHZ gives

the maximum analog bandwidth of 10 GHZ and the maximum number of bits of N = 13.

The light limited region, where N >13, the bandwidth is related to the number of bits by

the following formula: BW = (c/2np) x $(1/2^N)$, where, c is the speed of light, n reflects how

slow the transmission line phase velocity is relative to c, and where n is assumed to be 3, and p is

the pitch. From this formula one obtains N=17 bits at BW of 1GHz.

A long length limitation in Fig. 5 is obtained because the above formula breaks down due

the constraint that the transmission line length cannot be indefinitely long. Based on intuition,

practical constraints such as microfabrication, electron beam scan distance, beam defocusing and

others, the maximum transmission line length is about 10cm, in this case, the A/D converter

performance has a 500MHz bandwidth at 18 bits of resolution.

It is possible to improve the performance even further as shown by the dashed curve in

Fig. 5 by reducing the pitch to smaller than 0.5 micron and increasing the electron beam

deflection bandwidth beyond 20 GHZ. Both are possible with sophisticated lithography and

microfabrication techniques, as well as refined design of electron beam deflection systems.

From the foregoing analysis, it is clear that the invented electron beam A/D converter has

orders of magnitude higher performance than the most advanced JJ-based circuits. The

possibility of obtaining analog bandwidths of 10GHz at 13 bits or 1GHz at 17 bits is impossible

to contemplate by other technologies. The key factor to achieving such ultra-high performance

levels is the ability to create electron beam deflection circuits of bandwidths in excess of 10GHz.

This was demonstrated by S. M. Kocimski (IEEE Transactions On Electron Devices, Vol. 38.

page 1524, June, 1991). Another important advantage of this new concept is that Josephson

junctions can be of the weak link type instead of the tunnel junctions having sharp quasi particle tunneling components. The weak link can readily be made using HTC superconducting materials making it possible to use cooling at 77°K with a miniature refrigerator as shown in Fig. 6.

A primary concern with achieving deflection bandwidths of 20GHz and beyond relates to the linearity over the dynamic range of 2^N when N > 10. Fortunately, the disclosed A/D converter architecture can address this at the superconducting chip. Instead of having the rows repeat periodically with pitch p, certain groups of rows will have variable spacing determined by measurements of the non-linearity. This scheme, therefore, serves to minimize the non-linearity.

A preferred embodiment of an ultra-high performance A/D converter system 70 is schematically illustrated in Fig. 7. The A/D converter system 70 includes three major subsystems. An electron beam subsystem 76 generally comprises known electron beam generating systems capable of delivering an electron beam, for example, having about a 0.5 micron diameter, 0.1 μA, and voltage in the 1-5 KV range depending on the analog bandwidth desired. Depending on the performance, the X, Y deflection circuits are designed to achieve bandwidths in the range of 100MHz to 20GHz.

A superconducting transmission line chip 76 is also provided, which utilizes high T_c superconducting transmission lines and weak link devices providing linearized transmission generally as described above with respect to Figures 2-4, along with appropriate insulator and resistor technologies and a regulated power supply. The chip 76 preferably includes wide bandwidth amplifiers to interface with room temperature electronics. The chip 76 should be packaged in a vacuum seal arrangement such that the top surface is in the vacuum and exposed

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to the electron beam excitation while the other surface is thermally connected to a cooling

subsystem 78

–The cooling subsystem 78 is provided to compensate for the dissipation from the

superconducting circuit of a fraction of a milliwatt of power. Accordingly, the cooling constraint

is not severe. Cooling may be accomplished conveniently using, for example, a miniature

Stirling dosed-cycle refrigerator shown in Fig. 6, which is well known.

Additional electronics, not specifically shown in Fig. 7, such as linear-wide bandwidth

amplifiers, sync generators and room temperature interface electronics, such as memory buffers

and processors, also may be included as neede dfor the particular applaiciton.

The modifications to the various aspects of the present invention described hereinabove

are merely exemplary. It is understood that other modifications to the illustrative embodiments

will readily occur to persons with ordinary skill in the art. All such modifications and variations

are deemed to be within the scope and spirit of the present invention as defined by the

5   accompanying claims.

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